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Research and Practice of Response Control for Tall Buildings in Mainland China

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Abstract

In the recent two decades a large amount of tall buildings have been constructed in Mainland China, offering good opportunities of research and practice for Chinese researchers and practioners in the field of structural engineering. Some research and practice achievements of response control for tall buildings in Mainland China in recent five years are introduced here, focusing on the performance-based seismic analysis and design of code-exceeding tall building aiming to design structures with predictable seismic performance in the future earthquake, shaking table model tests on complex tall buildings to evaluate the seismic performance of structures and accordingly revise the structural design, and the application of structural control technologies to better protect tall buildings from winds and earthquakes. Some typical examples of practical application, such as application of active tuned mass dampers (ATMD) in Shanghai World Financial Center Tower and application of deformation-related with damping and stiffness dampers in Zhengda Himalaya Hotel, are presented.

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Keywords: Tall buildings; Performance-based seismic design; Shaking table test; Structural control

1. Introduction

With the rapid economic growth and urbanization, the high-rise construction boom started from 1990s in Mainland China. Owing to the wide variety of social requirement for commercial or aesthetic purposes, the limited availability of land, and the preference for centralized services, the height of tall buildings has grown taller, and the configuration as well as structural system has become more complex in recent years, which brings more difficulties in structural analysis and design. The seismic safety of tall buildings has attracted extensive attentions of the local government and researchers due to the fact that most of the tall buildings having been completed or being under construction are located in earthquake prone areas. Furthermore, a large amount of super tall buildings concentrate in the east coastal areas where the effects on structures by winds are equally important. The most effective way to better protect structures, along with their occupants and contents from earthquakes and winds could be through the development of more

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reliable code provisions and design methods than those currently available, and the implementation of the advanced technology in construction. The research of response control for tall buildings under earthquakes and winds has been highlighted and some progress has been made in this field (Lu et al 2007a; Lu et al 2009). Based on the research achievements, the structural design methods and control techniques for tall buildings have been improved. Some structural control technologies have been applied in engineering practice. Some research and practice work of response control for tall buildings in Mainland China in recent five years are introduced here.

2. Performance-based seismic analysis and design of code-exceeding tall buildings

Chinese regulations provide high prescriptive provisions, such as the height limits on various structural systems in each seismic intensity zone, plan and vertical regularities, and various response limits. Tall buildings satisfying the regulations can be designed according to the regulations. Building codes provide the minimum requirements for the design of structures to ensure the safety of the life and property. Tall buildings not satisfying the regulations are called "code-exceeding" and are required to conduct expert panel review called "Review on Seismic Fortification of Code-exceeding Tall Buildings" at the end of the preliminary design phase. In Mainland China in recent years, performance-based seismic analysis and design approach has been highly recommended to employ especially in code-exceeding tall buildings in order to control efficiently the seismic damage and economic losses, to promote the implementation of the advanced technology in construction, and to meet the diverse needs and objectives of the owners, users and society. In Shanghai, Seismic Design Guidelines for Tall Buildings beyond the Scope of Design Codes issued by Shanghai Urban Construction and Communications Commission (Lu 2009) are the present unique design guidelines concerning code-exceeding tall buildings in Mainland China. The performance-based seismic design approach specified in the guidelines is introduced as follows.

2.1 Categories of code-exceeding tall buildings

Non-prescriptive or code-exceeding tall buildings fall into one of the following categories:

(1) Tall buildings with heights exceeding the applicable limits for the respective structure type as specified in the guidelines.

(2) Tall buildings with three or more of plan or vertical irregularities. The irregularities involve drastic changes in geometry, interruptions in load paths, discontinuities in both strength and stiffness, disruptions in critical regions by openings, large eccentricity between the rigidity centre and mass centre, etc. The allowable limits are specified in the guidelines.

(3) Tall buildings with one or more severe plan or vertical irregularities list in the guidelines. Sever irregularities include severely over limit of the above items, transfer floor at high level, multiple complex structure, etc.

(4) Other tall buildings. These are tall buildings which have new or undefined structural system that are not addressed in current codes, or have long spans and high occupancies such as train stations, stadiums, department stores, exhibition halls, airports, etc.

2.2 Performance objectives

Three earthquake design levels, i.e. frequent earthquake (63% probability of exceedance in 50 years or 50 year return period), basic earthquake (10% in 50 years or 475 year return period), and rare earthquake (2% to 3% in 50 years or 2475 year return period), are considered in Mainland China. The performance objectives should be enhanced for code-exceeding tall buildings. The relationships between the performance levels and earthquake design levels are summarized in Table 1. The seismic fortification category of buildings is classified into four grades according to the importance of building and the consequence of earthquake disasters. Type A is the highest grade. For tall buildings, the lowest grade, Type D, is excluded.

Table 1: Seismic performance objectives for code-exceeding tall buildings

Seismic fortification category		Seismic performance level		
		Frequent earthquake	Basic earthquake	Rare earthquake
A		Fully operational	Fully operational	Operational
B		Fully operational	Operational	Life safety
C	Buildings with height exceeding code limit and regular RC structure	Fully operational	Repairable	Life safety
C	Buildings except above	Fully operational	Operational	Life safety

2.3 Design criteria and procedures

The design criteria are established corresponding to the desired performance objectives. These minimum acceptance criteria ascertain that the performance objective be accomplished. The criteria are set in terms of limit values of axial load ratio (specified for RC columns and shear walls), stresses, inter-story drift ratios, etc. The design philosophy of weak beam and strong column, weak flexural strength and strong shear strength, and weak member and strong joint, is commonly employed to adjust the strength and then the reinforcement. In addition, the constructional measures, such as minimum reinforcement ratio, minimum material strength grade, reinforcement detailing, etc., are required to reduce structural damage.

The seismic design procedures consist of two design phases. In the first phase, the seismic performance objectives are selected and elastic analysis under the frequent earthquake is performed to determine the dimensions and reinforcement of structural members by modal response spectrum analysis using elastic design spectra. In the second phase, the seismic performance of the target building is evaluated by numerical analysis ranging from simple frame procedures to an elaborate finite element analysis. Nonlinear analysis should be properly substantiated with respect to the seismic input, the constitutive model used, the method of interpreting the results of the analysis and the requirements to be met. Nonlinear dynamic analysis should be performed for the buildings with the height more than 200 m. Buildings higher than 300 m are required to be analyzed using two or more different computer programs to validate the results. The earthquake responses, plastic mechanism, distribution of damage, etc., are estimated against the preset allowable limit. If necessary, structural testing including joint, member, and integral structural model test should be conducted to study the structural behavior and check the seismic performance directly. If the pre-defined seismic objectives can not be satisfied, design iteration should be done until satisfied. Figure 1 shows the flowchart of overall performance-based seismic design procedures.

3. Shaking table model tests on complex tall building

Structural model testing is often used to help structural engineers to directly acquire the knowledge about the prototype structure, especially in the case of complex tall buildings for which the numerical simulations are considered somewhat unreliable. Shaking table model test has been considered an economic and practical way to evaluate the seismic performance of structures. Many reduce-scaled structural models of complex tall buildings have been tested on the authors' laboratory. The model design and construction method, testing and analytic procedures, and measure techniques have been well developed. By shaking table tests, the earthquake responses and dynamic characteristics are obtained, the failure process and mechanism, and structural weak points are discovered, and then the overall seismic performance of the prototype structure is evaluated accordingly. Advices or suggestions are proposed as references for structural design to improve the seismic performance of structures. Some test results were also verified by in-site testing on completed real buildings (Lu et al 2007b). Some test results were also verified by numerical analysis (Lu et al 2007c). The shaking table model tests on three tall buildings conducted in this laboratory recently are introduced briefly here as typical examples.

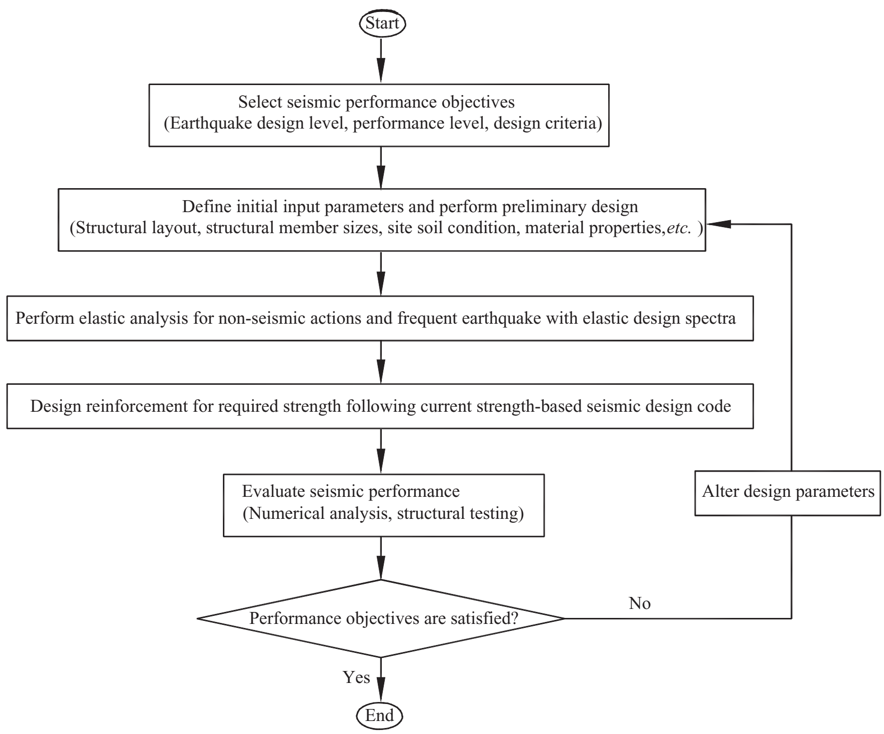


Figure 1: Flowchart of overall performance-based seismic design procedures.

3.1 Shanghai International Financial Center Tower

The total height of the 53-story building is 250 m above ground. The main structural system consists of steel reinforced concrete frame and RC core wall. It is a vertically irregular structure, due to a number of stiffened stories and a high-position transfer story to afford the substantial decrease of spacing between columns above the 39^{th} Floor level.

A 1/30-scale model as shown in Figure 2 was constructed and tested on the shaking table, subjected to a series of one and two-dimensional base excitations with gradually increased acceleration amplitude for four intensity levels, representing frequent, basic, and rare earthquakes of Chinese intensity 7, and rare earthquakes of Chinese intensity 8 respectively. El Centro wave (1940), Pasadena wave (1952), and Shanghai artificial wave, were used as input motions with PGA scaled according to the similitude relationship. No visible cracks occurred in the tested model under the ground motions of the first two intensity levels. The model slightly cracked under the ground motions of the third intensity level. Under the ground motions of the largest intensity level, most of the damages concentrated at the structural members located in the transfer as well as stiffened stories (from the 37th to 39th Floor level). The connection zones between the peripheral mega-columns and closely spaced columns were damaged seriously. The longitudinal bars buckled and cover concrete crushed and spalled in the closely spaced columns. Horizontal cracks occurred at the top of some mega-columns, as shown in Figure 3(a). Some steel members in the outrigger truss buckled, as shown in Figure 3(b). The arrangement of closely spaced columns are suggested to be adjusted and the ductility be increased accordingly. The design of the structural members and joints in the transfer story is also suggested to be improved. The maximum inter-story drifts and overall seismic behavior meet the requirements of Chinese seismic design code.

Figure 2: Tested model.

(a) Mega-column

(b) Outrigger truss

Figure 3: Damages in the tested model.

3.2 National hall of China pavilion for Expo 2010 Shanghai

The National Hall of China Pavilion for Expo 2010 Shanghai was designed with peculiar style and special structural system. The main structure is composed of four RC tubes with steel-concrete composite floors. Four cores with the same plan dimensions 18.6 m × 18.6 m were designed as the primary lateral resisting system. At the height of 33.3m, 20 inclined columns consisting of concrete-filled rectangular steel tube is placed on the perimeter of the cores as the vertical support of the big-span steel beams in the floors. The fundamental vibration mode of this structure is torsional, resulting in the period ratio between the first torsional mode and the first translational mode exceeding the limit value stipulated in Chinese design code. In addition, there is an atrium with dimensions 32.7 m × 32.7 m and the floors between the height of 38.7 m and 46.8 m are staggered, which results in the plan irregularity defined by the Chinese code.

A 1/27-scale model as shown in Figure 4 was constructed and tested on the shaking table subjected to a series of one and three-dimensional base excitations. The test procedures and the imputed motions are similar to above tests. No visible cracks occurred in the tested model under the ground motions of the first intensity level. After the input of ground motions of the second intensity level, several vertical cracks were detected at the ends of the coupling beams located between the 4th and 10th Floor. One inclined column slight twisted, which may be attributed to its instability. Under the ground motions with the third intensity level, both ends of most coupling beams below the 10th Floor showed vertical cracks (see Figure 5), and for those with sectional dimensions 800 mm×4500 mm at 10th Floor, diagonal cracks were observed (see Figure 6). However, previously observed twist of inclined columns did not develop further. Under the ground motions of the last intensity level, almost all the coupling beams within the core wall showed vertical cracks at both ends. Horizontal cracks and crushing of concrete occurred at the bottom of the core wall. Although the first mode is tortional, the actual torsional responses are not significant. The inter-storey drift and the overall seismic behavior meet the requirements of Chinese code. To improve its seismic performance, it is suggested to reduce the sectional dimensions of the coupling beams with large height at the level of 33.3 m and strengthen the transverse connection of inclined columns.

Figure 4: Tested model.


Figure 5: Cracks in coupling beams.

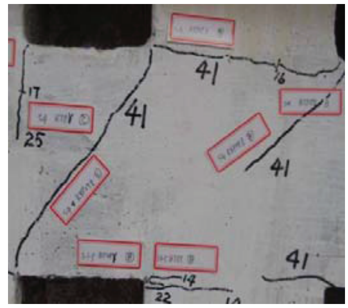


Figure 6: Cracks in coupling beams and walls

3.3 Shanghai Jiali Center

Shanghai Jiali Center has 58 stories above the ground and 4 stories underneath with the total building height of 260 m. The steel reinforced concrete frame and RC core structural system with a stiffened story at middle height was designed to resist the lateral and the vertical loads. There are two setbacks at the 21st and 31st Floor respectively, and two sets of inclined columns tilting from the 16th to 21st Floor and from the 21st to 22nd Floor. The structure is vertically irregular.

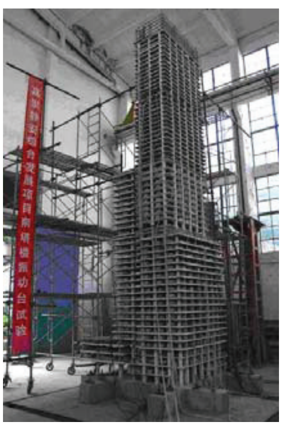


Figure 7: Tested model.


Figure 8: Crack in column.


Figure 9: Crack in wall.

A 1/35-scale model as shown in Figure 7 was constructed and tested on the shaking table subjected to a series of one and two-dimensional base excitations. The test procedures and the imputed motions are similar to above tests. No visible cracks were found in the model after the first two phases of test. After the third phase, several cracks were observed in the columns at the 2nd Floor. After the forth phase, significant damages occurred. In the stories adjacent to the setback of the 31st Floor, cracks appeared in some columns, and the concrete at the bottom of some columns crushed. The diagonal cracks run through the whole core walls in the setback story. The columns above the inclined columns of the 22nd Floor cracked, due to the complex load transfer path from inclined columns to the vertical ones. Figures 8 and 9 show the typical cracks in the columns and walls at 31st Floor. No damages were observed in the bottom shear walls and the truss members in the stiffened story. The maximum inter-story drifts and overall seismic behavior meet the requirements of the Chinese code. The ductility of the structural members at the setback of the 31st Floor is suggested to be improved to reduce the adverse impact brought by the abrupt stiffness alteration.

4. Structure control study with application

The structural control technology has been applied extensively to ensure the safety and serviceability of buildings against natural disasters. Generally, structural control technology for alleviation of wind or earthquake response of buildings can be categorized into three broad areas: base isolation systems, passive energy dissipation systems and active control systems. Of them, active control systems have still not been applied widely due to excessive cost and extra large power requirements. The other two have been considered as relatively mature technologies and already applied to a large number of buildings throughout the world. Two typical examples of application of structural control technology in tall buildings, one to resist winds, the other to resist earthquakes, are introduced as follows.

4.1 Application of ATMD in Shanghai World Financial Center Tower

The 101-story Shanghai World Financial Center Tower (SHWFC) is 492 m above ground, the tallest completed building in Mainland China. The perspective view of SHWFC is shown in Figure 10. The structure is diagonally symmetrical, as shown in Figure 11. Three parallel structural systems, the mega-frame structure consisting of the mega-columns, mega-diagonals, and belt trusses; the reinforced concrete and braced steel services core; and the outrigger trusses which create interactions between the services core and the mega-structure columns, are combined to resist vertical and lateral loads. Perimeter concrete walls locate at lower levels from the 1st to 5th Floor, and mega-columns are positioned at the corners of the building from the 6th Floor. Several stiffened and transfer stories in the structure are regularly spaced throughout the height of the building. One-story high belt-trusses and core transfer trusses are placed at each 12-story interval, whereas three 3-story high outrigger trusses spanning between the mega-columns and the corners of the services core are distributed evenly along the height. Both of the total height and irregularity exceed the code limit.

In order to mitigate wind-induced vibration, a set of two identical active tuned mass dampers (ATMDs) is installed at the 90th Floor (see Figure 12): under wind loading, the active control feature is enabled, while the active control feature becomes disabled under earthquake condition and the damping devices functions as passive tuned mass dampers (Mitsubishi Heavy Industries 2007). Figure 13 gives the working principle of ATMDs. The damping devices are installed along y axis. The vibration body, whose natural period is adjusted to the fundamental period of the building (y direction), is hoisted by the multi-sectional steel cables. The damping devices consist of two parts: multi-section vibration body and drive device. The control force of vibration body is obtained by the feedback motion state variables. These state variables include the acceleration of the floor on which the damping devices are set up, as well as displacement and speed of the vibration body. The designed travel stroke of the damping devices are 140 cm and the control stroke of the damping devices are 110 cm. In addition, to avoid excessively large displacement of the damping devices in seismic events, the devices are locked by locking devices on the driven screw when the vibration amplitude of vibration body exceeds 110 cm in the passive control state.

Figure 10: Perspective view of SHWFC. (Source: from public website)

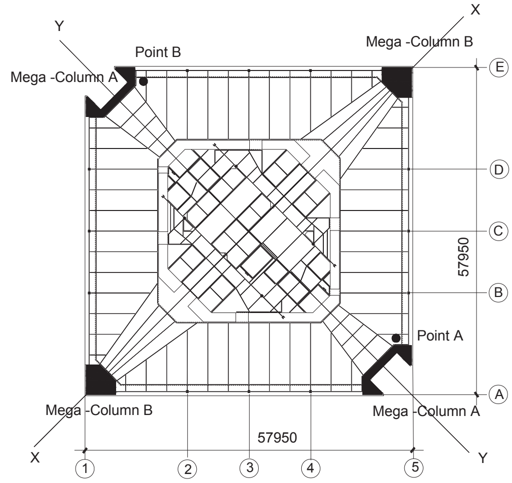


Figure 11: Standard structural plan.

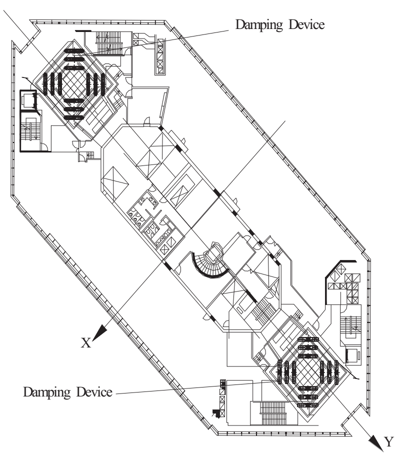


Figure 12: Floor plan of the 90th Floor.

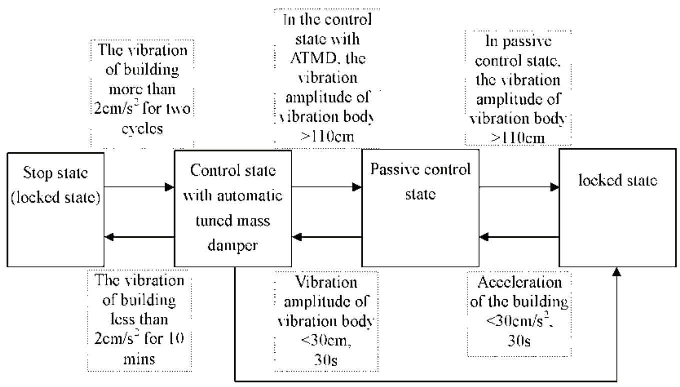
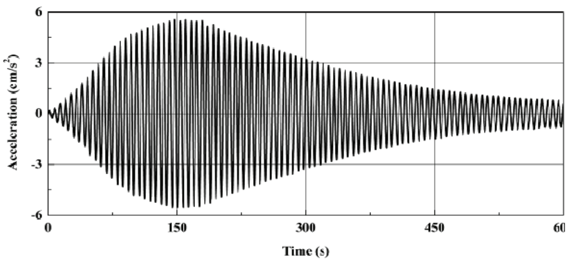


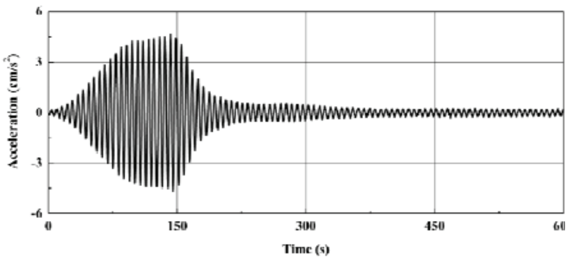
Figure 13: Working principle of ATMDs.

The analytical results of the vibration control are as follows: under the active control state with the effect of wind load of a one year return period, the maximum acceleration response of the 90th Floor decreases to 60% and root mean square of acceleration response decreases to 55%; under passive control state with the effect of wind load of a 10 year return period, the maximum acceleration response of the building decreases to 72~79% and the root mean square of acceleration response decreases to 72~74%; under locked state with the effect of wind speed of a 100 or a 200 year return period, no significant effect is obtained in the maximum acceleration response. When the active control features are disabled, the damping devices work as typical passive TMDs. The seismic performance of the structure with the TMDs is estimated. TMDs can reduce the vibration of the fundamental mode in very small degree. Since the fundamental mode of the structure does not dominate the response, vibration control directed toward this mode under seismic action would indeed be fruitless. The TMD has little effect on the seismic performance of the structure.

In order to verify the analysis results, site measurements under ambient and forced vibration condition were performed. The natural frequencies and damping ratios estimated in the analytical and experimental studies are almost identical with 0.3% error. The acceleration time history of the 90th Floor in X direction with and without active vibration control of the two types of forced vibration tests at amplitude of 5 gal is shown in Figure 14. With active tuned mass damper, the structural vibration is mitigated significantly. The damping ratio for the first mode (in Y direction) without active vibration control is 0.422% while the value increases to 3.404% with active vibration control. The damping ratio for the second mode (along x direction) without active vibration control is 0.459%, while the value increases to 3.865% with active vibration control. The damping ratio with vibration control devices increases by 8 times.



(a) ATMD off



(b) ATMD on

Figure 14: Acceleration time history of the 90th Floor along X axis under forced vibration.

4.2. *Application of Deformation-related Dampers in Zhengda Himalaya Hotel*

Shanghai Zhengda Himalaya Art Center as shown in Figure 15 consists of an office building (in the left), a multi-function hall (in the middle), and a five star hotel (in the right). Only the earthquake response control of the hotel is introduced here. The total height of the 22-story hotel is 98.7 m. The main structural system consists of RC frame and shear walls. The plan is a square with the side length of about 60 m. The structural plan layout of the 11th to 16th Floor is shown in Figure 16. There is a large opening in the center of the plan, leading to the plan irregularity. A transfer story is located at the 6th Floor, and the section of the RC tube from the ground to the 6th Floor is abnormal, resulting in the vertical irregularity. The ratio of the maximum floor displacement to the average one which reflects the tortional response is up to 1.31 under the earthquake.

To improve the seismic performance of the building, 36 sets of deformation-related with damping and stiffness damper distributed from the 10th to 17th Floor, half in the X direction and half in the Y direction, are installed in the structure. As a metallic damper classified as the displacement-dependent type damper, the damper consists of a series of low yielding strength steel holed plates wherein the bottom of the plates are attached to the top of a chevron bracing arrangement and the top of the plates are attached to the floor level above the bracing. As the floor level above deforms laterally with respect to the chevron bracing, the steel plate is subjected to shear force. The shear force induces bending moment over the height of the plate, with bending occurring about the weak axis of the plate cross section. The dissipated energy in the damper is the result of inelastic behavior and thus the damper will be damaged during an earthquake and need to be replaced. A 1/20-scale model of the structure with the dampers (see Figure 17) were constructed and tested on the shaking table. The scaled model of the damper was first tested under cyclic loading, as shown in Figure 18. The dimensions of the damper model are shown in Figure 19. The damper has good energy-dissipation energy, which is demonstrated by the force-displacement curve obtained by the test (see Figure 20). The shaking table tests verify that the structure with dampers has good seismic performance and can meet the code requirements.

Figure 15: Perspective view of Shanghai Zhengda Himalaya Art Center.

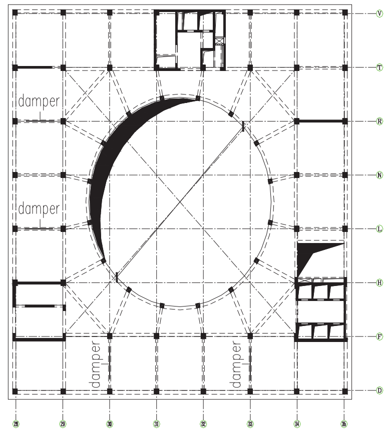


Figure 16: Structural plan layout of the 11th to 16th Floor.

Figure 17: Tested model in the shaking table.

Figure 18: Cyclic loading test on model damper.

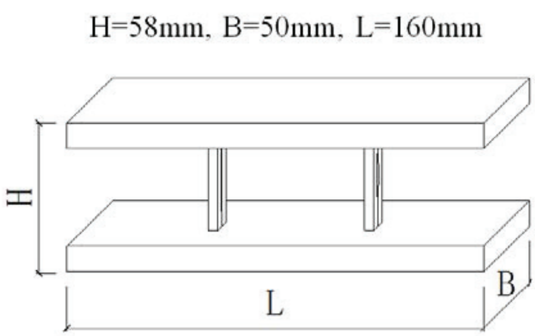


Figure 19: Dimensions of model damper.

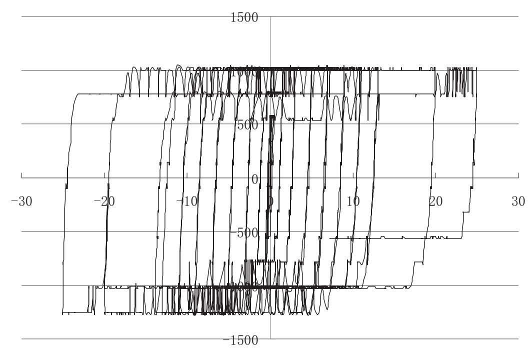


Figure 20: Force-displacement hysteretic curve.

5. Conclusions

Some research and practice achievements of response control for tall buildings under winds and earthquakes in Mainland China are presented here. A general performance-based seismic analysis and design approach for code-exceeding tall buildings is introduced. By the incorporation of performance-based seismic design into the current seismic design code, it becomes much more possible for designers to intentionally control the damage levels of structures within acceptable range during earthquakes of different intensities. In Mainland China shaking table tests on the scaled model have been extensively employed to evaluate the overall seismic performance of complex tall buildings and accordingly revise the structural design to meet the performance objectives. On the other hand, the structures could be protected from earthquakes and winds with the aid of structural control technologies. There has been steady progress in research and development of structural control techniques in Mainland China. This technology is still evolving with the aid of other technologies. The research work is generally combined with engineering application and can be transformed for the actual needs of engineering practice. Most of the research results have been applied in engineering practice successfully.

Acknowledgments

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